The possible role of ground-based support for a better determination of asteroid physical parameters based on Gaia data.

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Introduction

The determination of bulk physical properties for the largest possible number of asteroids which will be observed by Gaia is an important task which can be made easier by performing some dedicated ground-based observing campaigns. The proposed actions, consisting of applications of different observing techniques, primarily photometry and polarimetry, are not expected to be triggered by Gaia alarms, nor do they require in principle prompt reaction times triggered by special circumstances. We deal here, conversely, with the problem of improving the amount and quality of data at our disposal concerning some properties of a suitable sample of asteroids, to be used for the purposes of a better calibration of some fundamental relations which are commonly used in asteroid science.

We remind that the excellent astrometric, photometric and spectrophotometric performances of Gaia are expected to make it possible to obtain direct size measurements of main belt asteroids larger than about 25 km, rotation properties and overall shapes for a number of the order of 10^4 objects, and reflectance spectra and taxonomic classification for a number of asteroids which could be 10 times larger. In addition to this, we will have also a formidable improvement in the knowledge of asteroid orbital parameters, and the derivation of mass estimates for a number expected to be of the order of 100 individual asteroids, without taking into account the masses of binary systems derived by determination of their mutual orbital periods. For a small number of near-Earth asteroids, moreover, it is expected that a measurement of the drift in orbital semi-major axis due to the Yarkovsky effect might also be measurable.

Two basic parameters, however, namely the albedo and absolute magnitude, will be difficult to determine based on Gaia data, due to reasons essentially related to the fact that Gaia will never observe asteroids close to solar opposition. The situation, however, is not totally hopeless, and there are possible ways to determine, at least, the albedo. The albedo quantifies the surface reflectance at visible wavelengths, and is a very important physical parameter, being determined by surface composition, roughness and texture, and by the overall thermal history of the body. In this paper we explain why some dedicated ground-based observing campaigns are strongly recommended in order to improve our capability to derive from Gaia data reasonable estimates of the albedo, if not also of the absolute magnitude, for many objects.

1. The size - absolute magnitude - albedo relation

A fundamental relation in asteroid science is the one between size, absolute magnitude and albedo, which can be written as:

$$\log(D) = 3.1236 - 0.2H - 0.5\log(p_V) \tag{1}$$

in the above expression, D is the diameter of the object in km, assuming for sake of simplicity a spherical shape; H is the absolute magnitude (the magnitude which would be measured in standard V light if the object was observed at unit distance from both the Sun and the observer and at zero phase angle, that is at ideal solar opposition; p_V is the geometric albedo, defined as the ratio between the actual brightness in V light at zero phase angle to that of an idealized flat, fully reflective, diffusively scattering (Lambertian) disk with the same cross-section. The value of the constant (3.1236) is a consequence of the definition of magnitudes and of the fact of working in standard V light.

Equation 1. is used to derive one of the three parameters, being provided estimates for the other two ones. For instance, p_V can be derived by means of measurement of linear polarization of asteroid visible light. If H is known, this makes then possible to derive the size. Conversely, thermal radiometry measurements are used to derive reliable estimates of the size. If the absolute magnitude is also known, this leads to determination of the albedo. The most recent application of this procedure has been the huge catalog of asteroid albedos derived from WISE data ([4]). However, albedos derived from thermal IR data alone are subject to significant uncertainties, since the computation requires the use of values of the absolute magnitude H which are both affected by large error bars, and correspond in general to different apparent illuminated areas with respect to those visible at the epochs of thermal IR observations. The bottom line is that even after the WISE mission it certainly makes still sense to try and obtain independent albedo measurements for large data sets of objects.
In the case of Gaia, which has neither polarimetric nor thermal IR capability, it would seem that the situation is hopeless. On the other hand, Gaia is expected to measure the sizes of about $1,000$ main belt asteroids. In the case that the absolute magnitude of these objects could also be derived from Gaia photometric data, this would lead immediately to a derivation of the albedo p_V. Moreover, we will see that there is the possibility that photometry alone could provide some opportunity to derive the albedo in a way which will be explained below. What is important, is that in any case, the possibility to derive values of H and p_V from Gaia data will significantly depend on evidence coming from extensive ground-based observations.

1.1 *Asteroid phase-magnitude curves*

The absolute magnitude H is the magnitude at zero phase angle, the latter being defined as the angle between the directions to the Sun and to the observer as measured from the asteroid. In the real world the asteroid can never be observed at exactly zero phase angle (perfect solar opposition). In many cases, even at opposition the phase angle is far from zero, since the objects are not located on the ecliptic, therefore they are not in the plane containing the observer and the Sun. The absolute magnitudes of the asteroids must then be found by means of some extrapolation of the relation between magnitude and phase angle which can be obtain by photometric observations covering different phase angles around a given opposition (the so-called asteroid phase curves). The morphology of the phase curves consists usually of a linear relation over a wide range of phase angles (the object becoming fainter for increasing phase angle). Unfortunately, at small phase angles, however, below 5 - 7 degrees, a non-linear brightness surge is usually observed. This phenomenon is commonly called the "opposition effect".
Due to the fact that Gaia will never observe asteroids at solar elongations larger than 135 degrees, the opposition effect will not be observed by Gaia. Any hope to derive the absolute magnitude H must therefore be based on the availability of photometric systems to describe the behavior of the asteroids, which are required to be able to derive a correct estimate of the opposition effect based on photometric data collected at phase angles much larger. Recently, [3] have shown that the photometric system which has been adopted for many years to describe the phase curves of the asteroids, namely the so-called (H,G) system, is not sufficiently reliable for the purposes of Gaia. On the other hand, the same authors have developed a new photometric system, called (H,G_1,G_2) which should be more suitable to derive a reasonable estimate of H, even when one has at disposal only observations not covering the opposition effect. As explained by [3], however, the new photometric system has been developed having at disposal a fairly limited number of high-quality phase curves. The base functions which define the (H,G_1,G_2) system can, on the other hand, be easily improved provided new high quality phase curves are made available. This is an ideal task for ground-based observing programs, even using telescopes of modest aperture. In this way, the absolute magnitudes of objects whose sizes will be directly measured by Gaia can in principle be derived, using the (H,G_1,G_2) system, and the Gaia photometric data covering five years of sparse observations. For these objects, therefore, the albedo could also be immediately derived once the absolute magnitude is known. The complication here is that H is not really a constant for any given object, but varies in different oppositions depending on the so-called aspect angle, namely the angle

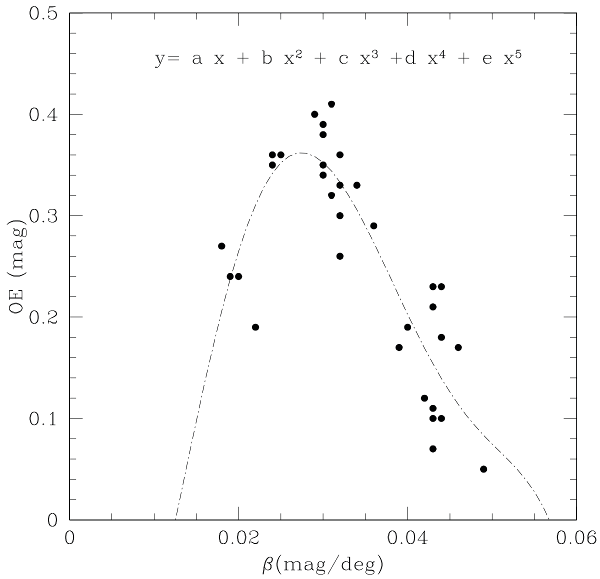

Figure 1: Tentative fit of the photometric opposition effect *versus* slope of the magnitude - phase curve for the sample of asteroids analyzed by [1]

between the polar axis and the direction to the observer, as measured from the asteroid. Since asteroids are not spherical, the illuminated surface area visible from an observer changes as a function of the aspect angle. Gaia sparse photometric data will be inverted to derive the polar axis direction and overall shape of the objects, but it is clear that the uncertainty on the inversion, and on the derivation of the absolute magnitudes, put some practical limits to the reliability of absolute magnitudes and albedos derived in this way. On the other hand, some alternative ways to solve the problem may exist, as explained in the next Subsection.

1.2 *The possible use of photometric data to derive asteroid albedos*

Although a single magnitude measurement is certainly not sufficient to derive the albedo, since the magnitude depends also on the size, there is the possibility that the phase curves, obtained by means of multiple observations at different phase angles, might be used to derive the albedo. An extensive study of the properties of asteroid phase curves was published by [1]. These authors described the phase curves using a simple mathematical description, consisting of a linear term plus an opposition surge occurring at low phase angles. This is interesting from the point of view of Gaia applications, because the slope of the phase curves will be derived by inversion of Gaia sparse photometric data. In [1], the authors looked for possible relations between the slope of the linear part and the extent of the opposition effect, but they did found that the relation is complicated and not monotone, as shown in Figure 1 in which a tentative polynomial fit is also shown. This figure shows that the extent of the opposition effect will hardly be reliably obtained from the linear slope of the phase curves derived from Gaia data. What is more interesting and promising, however, is that [1] found a possible relation directly linking the linear part of the phase curves and the albedo. The authors express this relation as:

$$\beta = 0.013(\pm 0.002) - 0.024(\pm 0.002)\log(p_V)$$

where β is the slope of the linear part of the phase curve. The above relation is based on fairly noisy data (see Figure 4 in [1]), but it is potentially extremely useful for Gaia. In particular, because β can potentially be obtained for several thousands of objects, this would make it possible to derive for these same objects an albedo estimate. In this case, the Gaia albedo data-base would become a very significant achievement, even without being able to derive at the same time also the absolute magnitude of the

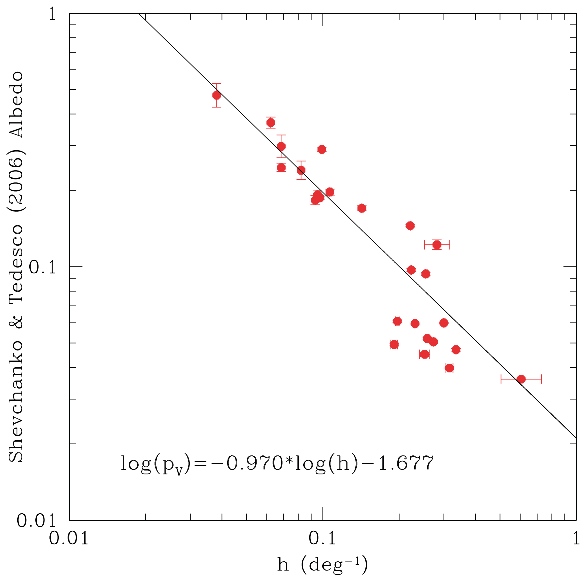

Figure 2: The most recent calibration of the slope -albedo relation used in asteroid polarimetry [2]. ST refers to the asteroid albedo data set published by [5].

objects.

1.3 *Asteroid albedos from polarimetry*

Whatever technique will be applied to derive asteroid albedos from Gaia data, the reliability of the results will have to be determined by means of comparisons with high-quality albedo determinations obtained for some sample of selected objects by means of other techniques.
In this respect, asteroid polarimetry seems to be the best possible options to produce a set of asteroid albedos to be compared with Gaia-based determinations. The relation between the polarization properties and the albedo of atmosphereless solar system bodies have been known since decades, and will not be discussed here. We will limit ourselves to mention that, historically, the albedo has been derived from measurements of the so-called "polarimetric slope" (usually indicated as h), which corresponds to the slope of the linear relation which is found to describe the phase - polarization curves around phase angles larger than about 15 degrees. One of the major problems in asteroid polarimetry has always been that of finding a good calibration of the adopted slope - albedo relation. The most recent, updated calibration has been recently provided by [2], using data which are shown in Figure 2. In this Figure, the vertical axis shows the albedos for objects of the list published by [5], which is thought to include the most reliable albedo estimates currently available for the asteroid population, being based on reliable H values and sizes directly and accurately determined by either *in situ* exploration by space probes, or observations of stellar occultations.

Conclusion

Ground-based observing campaign will be very a very useful support of the activities of determination of asteroid physical properties from Gaia data. At least three major tasks are suggested here:

1. Photometric measurements aimed at obtaining new high-quality phase -magnitude curves of objects which still lack them, to improve the H,G_1,G_2) system, and to derive also new reliable measurements of the linear part of the phase curves of objects with well determined albedo.

2. Measurements of new phase curves of objects already observed in the past, in order to check that the slope of the linear part (β) and/or G_1 and G_2 do not vary as a function of different aspect angle at different oppositions.

3. Polarimetric measurements aimed at further improving the calibration of the slope -albedo relation.

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